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STRENGTH AND LIFE ASSESSMENT REQUIREMENTS FOR LIQUID FUELED SPACE PROPULSION SYSTEM ENGINES

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(Inch Pound/Metric)

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FOREWORD

This standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities.

This standard establishes the strength and life (fatigue and creep) requirements for NASA liquid fueled space propulsion system engines. This document specifically defines the minimum factors of safety to be used in analytical assessment and test verification of engine hardware's structural adequacy.

Requests for information, corrections, or additions to this standard should be submitted via "Feedback" in the NASA Technical Standards System at http://standards.nasa.gov.

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Strength and Life Assessment Requirements for

Liquid Fueled Space Propulsion System Engines

1. SCOPE

This standard provides strength and life assessment requirements for National Aeronautics and Space Administration (NASA) liquid fueled space propulsion system engines. "Life," as used in this standard, refers to fatigue and creep. The requirements address analyses and tests to qualify an engine structurally. The total system requirements for engine hot-fire tests are not addressed in these requirements; however, a minimum number of such tests must be conducted in conjunction with structural analyses and tests to qualify the engine structurally. These requirements define the minimum structural requirements acceptable to NASA. These requirements specify analyses and test factors, margins, and other parameters where appropriate. In some cases, these requirements are expressed by reference to other standards.

1.1 Purpose

The purpose of this standard is to provide a consistent set of requirements to be used in designing and assessing liquid fueled space propulsion system engines. These requirements are intended to provide strength and life criteria which, in conjunction with other good engineering practices, will assist the program in meeting engine performance goals.

1.2 Applicability

This standard may be cited in contract, program, and other Agency documents as a technical requirement. The full requirements of this standard shall be addressed for liquid fueled space propulsion engines of 6K pounds thrust or more, and applied to smaller engines as required. Individual provisions of this standard may be tailored (i.e., modified or deleted) by contract or program specifications to meet specific program/project needs and constraints. Tailoring shall be formally documented and approved as part of program/project requirements.

The requirements in this standard apply to liquid fueled engine hardware used for NASA spaceflight missions. This standard presents acceptable minimum factors of safety for use in analytical assessment and test verification of the flight hardware's structural adequacy. Designs must generally be verified by both analyses and tests.

In general, no distinction is made between engines to be used for transporting personnel or those used for transporting hardware only. Engines for flight systems transporting personnel shall be subjected to additional verification and/or safety requirements (such as fracture control) that are consistent with the established risk levels for mission success and flight crew safety.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this standard as cited in the text of section 4. The latest issuances of cited documents shall be used unless specified by version control descriptor. The applicable documents are accessible via the NASA Technical Standards System at http://standards.nasa.gov, directly from the Standards Developing Organizations (SDOs), or other document distributors.

2.2 Government Documents

Department of Defense (DoD)

AFSPCMAN 91-710	Range Safety User Requirements Manual
DOT/FAA/AR-MMPDS-01	Metallic Materials Properties Development and Standardization (MMPDS)
MIL-STD-1522	Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems

National Aeronautics and Space Administration (NASA)

MSFC-DWG-20M02540	Assessment of Flexible Lines for Flow Induced Vibrations
NASA-STD-5005	Ground Support Equipment
NASA-SP-8007	Buckling of Thin-Walled Circular Cylinders
JSC 08307	Criteria for Preloaded Bolts

2.3 Non-Government Documents

**American National Standard Institute (ANSI)/
American Institute of Aeronautics and Astronautics (AIAA)**

ANSI/AIAA S-080	Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
ANSI/AIAA S-081	Space Systems – Composite Overwrapped Pressure Vessels (COPVs)

2.4 Order of Precedence

In the case of conflict, the technical requirements of this standard take precedence.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standard Institute
CDR	Critical Design Review
COPV	Composite Overwrapped Pressure Vessels
DoD	Department of Defense
ECF	Environment Correction Factor
FAF	Fatigue Analysis Factor
FOS	Factor of Safety
FSE	Flight Support Equipment
GSE	Ground Support Equipment
HCF	High-Cycle Fatigue
LCF	Low-Cycle Fatigue
MDC	Maximum Design Condition
MDP	Maximum Design Pressure
MEOP	Maximum Expected Operating Pressure
MMPDS	Metallic Materials Properties Development and Standardization
MS	Margin of Safety
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
PDR	Preliminary Design Review
SAP	Structural Assessment Plan
SDO	Standards Developing Organization

3.2 Definitions

Acceptance Test: A structural or pressure test conducted on the flight article to levels higher than Maximum Design Condition (MDC), Maximum Expected Operating Pressure (MEOP), etc., to verify material quality and workmanship.

Burst Factor: The burst factor is a multiplying factor applied to the Maximum Design Pressure (MDP) to obtain the burst pressure.

Burst Pressure: Minimum pressure level at which rupture of the pressurized hardware occurs.

Creep: A time-dependent deformation under load and thermal environments that results in cumulative, permanent deformation.

Design Service Life: See "Service life."

Development Test: A structural test (such as a pressure test) conducted on components to assess design concepts and guide the design.

E: Modules of elasticity.

Engine: The engine would generally include the nozzle, thrust chamber, pumps, and 'local' valves, regulators, plumbing, etc., unless otherwise defined by program and/or contract.

Factor of Safety (FOS): A multiplying factor to be applied to MDC, MDP, etc., loads or stresses for analytical assessment (design factor), or test verification (test factor) of design adequacy in strength or stability.

Failure: Rupture, collapse, or cracking at ultimate or less severe load, or permanent deformation greater than 0.2 percent at or less than the yield load. Also, "failure" is any permanent deformation that adversely affects the fit, form, function, or integrity of a structure at or less than the yield load.

Fatigue: In materials and structures, the cumulative irreversible damage incurred by the cyclic application of loads and environments. Fatigue can initiate cracking and cause degradation in the strength of materials and structures.

Fatigue Analysis Factor (FAF): A factor to compensate for large changes in life that occur due to small changes in stress. It is applied to the limit stress/strain prior to entering the S-N design curve to determine the fatigue life. The FAF shall be

FAF = 1.25 Rotating components
FAF = 1.15 Non-rotating components

Ftu: Ultimate strength.

Fty: Yield strength.

Hazard: A condition that is likely to result in personnel injury or catastrophic failure of an engine, vehicle, payload, or other facility.

Hot-Fire Test: A test of the engine propulsion systems and components by an actual firing of the engine, simulating flight conditions.

Limit Load: The same as the MDC load. See section 4.2.1.1.

Maximum Design Condition (MDC): The MDC is the most severe environment specified for the engine and its components.

Maximum Design Condition Load: Each engine program must define this load condition, but it should be based on the most critical condition, considering all loads and combinations of loads and environments that the engine and its components are expected to experience and that they must survive without failure. All phases in the life of the hardware including fabrication, assembly, testing, transportation, ground handling, checkout, firing, launch, flight, return, etc., should be considered in defining the MDC load. See section 4.2.1.1.

Maximum Design Pressure (MDP): The highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Transient pressures should be considered. Where pressure regulators, relief devices, and/or a thermal control system (e.g., heaters) are used to control pressure, collectively they must be two-fault tolerant from causing the pressure to exceed the system's MDP. The effects of maximum ullage pressure, fluid head due to vehicle quasi-static and dynamic accelerations, slosh, pressure transients and oscillations, temperature, and operating variability of regulators or relief valves are included in the MDP. When determining MDP, consider the maximum temperature to be experienced during an abort to a site without cooling facilities.

Maximum Expected Operating Pressure (MEOP): The maximum pressure expected to occur on a component in association with its applicable operating environments during its service life.

Net-Section Failure: A ductile mode of failure in which the net cross section loses its capability to sustain the mechanical load. The applied mechanical load is checked against the net-section failure load. Refer to table 1.

Point-Strain Failure: A ductile mode of failure in which a crack is initiated at a point in the structure by local concentrated total (elastic plus plastic) strain due to MDC loads. The maximum total concentrated strain at a point due to MDC loads is checked against the ultimate strain capability. Refer to table 1.

Point-Stress Failure: A brittle mode of failure in which a crack is initiated at a point in the structure by local concentrated stress due to MDC loads. The maximum concentrated stress at a point due to MDC loads is checked against the ultimate stress capability. Refer to table 1.

Pressure-Loaded Component/Structure: A component/structure not intended to store a fluid under pressure but experiencing significant pressure loads that may be in addition to other mechanical and thermal loads. The pressure-loaded component/structure is generally considered to be part of the engine. Turbine blades, pump housings, and main combustion chambers are typical examples. These components are analyzed and tested using the factors in table 1 for general metallic components and structures or for composite/bonded structures, as appropriate.

Pressure Vessel: A container designed primarily for pressurized storage of gases or liquids, and also carrying out one of the following:

a. Stores energy of 14,240 foot-pounds (19,310 Joules), or greater, based on the adiabatic expansion of a perfect gas.

b. Holds a gas or liquid at a MDP in excess of 15 psia (103.4 kPa) that will create a hazard if released.

c. Has an MDP greater than 100 psia (689.5 kPa).

Pressurized System: An interrelated configuration of pressurized components and/or pressure vessels.

Proof Factor: A multiplying factor applied to the MDC load, MDP, etc., to obtain the proof load or proof pressure for use in a proof test.

Proof Test: A structural or pressure test conducted on the flight article to levels higher than MDC, MDP, etc., to verify material quality and workmanship. The terms "proof test" and "acceptance test" are interchangeable.

Qualification Test: A test conducted on a separate flight-like structural test article at levels higher than MDC loads and at the MDC environment to verify the design.

Quasi-Static Load: A time-varying load in which the duration, direction, and magnitude are significant, but the rate of change in direction or magnitude and the dynamic response of the structure are not significant.

Responsible Organization: The government or contractor organization that is directly responsible for hardware strength verification.

Safety Factors: See "Factor of Safety."

Service Life: All significant loading cycles or events during the period beginning with manufacture of a component and ending with completion of its specified use. Fabrication, testing, handling, transportation, lift-off, ascent, on-orbit operations, descent, landing, and post-landing events shall be considered in establishing the service life of a component.

Service Life Factor: A multiplying factor to be applied to service life to assess design adequacy in fatigue or creep.

Shall: Indicates mandatory requirement.

S-N: Stress versus cycles to failure data (most often a curve)

Ultimate Load: The product of the MDC load multiplied by the ultimate factor of safety (FOS).

Ultimate Strength: Corresponds to the maximum load or stress that a structure or material can withstand without incurring rupture, collapse, or cracking.

Yield Load: The product of the MDC load multiplied by the yield FOS.

Yield Strength: The maximum load or stress that a structure or material can withstand without incurring permanent deformation. (The 0.2 percent offset method is usually used to determine the load/stress.)

4. REQUIREMENTS

4.1 General Requirements

4.1.1 Strength and Life Assessments

The responsible design element personnel shall establish and maintain an effective program to assess and verify engine systems' structural integrity. This assessment shall generally include both analyses and tests and shall use the factors of safety specified in this document.

The engine shall be assessed at MDC loads using the factors specified in table 1. Analyses are to be performed using material properties and loads that correspond to the appropriate environment, and tests are to be run in the actual environment. In cases where the proper environments cannot be imposed or used, adjustments shall be made to account for their absence.

4.1.2 Ground Support Equipment (GSE) and Flight Support Equipment (FSE)

In general, the design of GSE and FSE shall not impose critical loads on the hardware. NASA-STD-5005, Ground Support Equipment, shall be used to establish the engine GSE and FSE general characteristics, performance, design, test, safety, reliability, maintainability, and quality requirements.

4.1.3 Transportation of Flight Structures

As a goal, flight structure design shall be based on flight loads and conditions rather than on transportation and handling loads. Transportation equipment design shall be such that flight structures are not subjected to loads more severe than flight design conditions. Transportation loads are a function of the transportation mode and shall include the steady-state loads plus dynamic, vibration, and shock loads determined by analyses or tests.

4.2 Detailed Requirements

4.2.1 Strength Analysis

Strength analyses are required for the engine components using the following criteria.

4.2.1.1 Load Conditions

The MDC load shall be used in the strength assessment of the engine components. Each engine program must define this load condition, but it shall be based on the most critical condition, considering all loads and combinations of loads and environments that the engine and its components are expected to experience and that they must survive without failure. All phases in the life of the hardware including fabrication, assembly, testing, transportation, ground handling, checkout, firing, launch, flight, return, etc. shall be considered in defining the MDC load.

Load types to be considered include mechanical and thermal (steady-state and transient). Mechanical loads include forces, moments, and pressures. The pressures may be MEOP or

MDP, as applicable. Mechanical loads may be static, quasi-static, sinusoidal, transient, shock, impact, vibratory, acoustic, or random. When various types of loads from different sources occur simultaneously, these loads shall be combined, as applicable, in defining the MDC load. MDC loads shall be derived for all load cycles of the hardware.

4.2.1.2 Materials

4.2.1.2.1 Material Properties for Analyses

All material selection and material properties (strength, mechanical, fatigue, creep, etc.) shall correspond to the manufacturing processes and environments at which the structure sustains loads, or they shall be conservative with respect to the environments. Typical or mean values shall be used for physical properties. For applications where failure of a single load path would result in loss of vehicle integrity (strength, fatigue, or creep), mechanical properties shall be equivalent to "A" basis allowable as defined in DOT/FAA/AR-MMPDS-01, Metallic Materials Properties Development and Standardization (MMPDS). Material "B" basis allowable values may be used in a redundant structure where failure of a component would result in safe redistribution of applied loads to other load-carrying members. Specifically, allowables shall be established for temperature, cyclic load, sustained load, and shock (both mechanical and thermal due to heating and chilling). The sensitivity of a component to fracture, embrittlement, and stress corrosion in an operational environment shall be rigorously established. For reusable and multi-mission hardware, these criteria are applicable throughout the design service life and all of the missions. Therefore, design considerations shall include material property degradation under the service environments.

4.2.1.3 Design and Analysis Thickness

Generally, the thickness used in strength and life calculations shall be chosen using the tolerance specified such that the calculated margin is the minimum. Actual as-built dimensions may be used in stress calculations when available. Potential structural erosion due to plasma environmental effects, atomic oxygen, ablative nozzles, etc. during the design life shall be included in the design and analysis of the structure.

4.2.1.4 Weld and Braze Joints

Design of welds/brazes shall include the effects on stress levels due to weld/braze bead stress concentrations, parent material misalignment/offsets, and residual stresses. The material properties used in the assessments of weld/braze joints (strength, fatigue, creep, etc.) shall be adjusted appropriately for weld/braze joint efficiency based upon the classification (and/or process verification) of the joint. Due to inherent problems with inspections and reliability, the use of spot welds is not permitted.

4.2.1.5 Buckling and Crippling

Ultimate loading shall not cause structural members that are subject to instability to collapse, nor shall buckling deformation from limit loads degrade the functioning of any system or produce unaccounted changes in loading. Evaluation of buckling strength shall include the combination of all loads from any source and their effects on general instability, local instability, and crippling. Buckling failure modes shall be considered for all structural components that are subject to compressive and/or shear in-plane stresses under any combination of ground loads, flight loads, or loads resulting from temperature changes. Design loads for collapse shall be ultimate loads, except that any load component that tends to alleviate buckling shall not be increased by the ultimate factor of safety. Destabilizing external pressure or torsional limit loads shall be increased by the ultimate FOS, but stabilizing internal-pressure loads shall not be increased unless they reduce structural capability. Analyses of buckling of thin-walled shells shall use appropriate “knockdown factors” (correlation coefficients) to account for the difference between classical theory and empirical instability loads. Typical knockdown factors are listed in NASA-SP-8007, Buckling of Thin-Walled Circular Cylinders.

4.2.1.6 Fasteners and Preloaded Joints

Bolt design and joint separation in preloaded joints shall be in accordance with NSTS 08307, Criteria for Preloaded Bolts. Alternative methods to NSTS 08307 require prior NASA approval. Design and test factors for fasteners and preloaded joints shall be as specified in table 1.

4.2.1.7 Hardware that Experiences Pressure Loading

4.2.1.7.1 Design Requirements for Pressurized Systems and Components

Pressurized systems and components for engines shall meet the requirements of ANSI/AIAA S-080 AIAA Standard for Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components and ANSI/AIAA S-081 Space Systems – Composite Over Wrapped Pressure Vessels (COPVs); MIL-STD-1522 Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems; and this document. When using these referenced documents for pressurized systems, substitute MDP for MEOP as applicable. Use MDP in all cases involving personnel safety.

4.2.1.7.2 Pressure-Loaded Components and Structures

By definition, a pressure vessel is a container used to store pressurized fluid at specific energy or pressure levels or fluid that would be hazardous if released. Liquid fuel engine components such as main combustion chambers, high-pressure pumps, etc. are not considered to be storage containers, so these components are not classified as pressure vessels. Such components as these are pressure-loaded components and shall be designed using the safety factors in table 1 for metallic or composite/bonded structures as applicable. Pressure-loaded components and structures shall be designed to MDC loads.

4.2.1.7.3 Flexible Hoses/Bellows

All flexible hoses and bellows shall be designed to exclude or minimize flow-induced vibrations in accordance with MSFC–DWG–20M02540, Assessment of Flexible Lines for Flow Induced Vibrations. In addition, flexible hoses and bellows shall meet the safety factors listed in table 1.

4.2.1.7.4 Inadvertent Pressurized Volumes

Compartments or volumes that can become inadvertently pressurized as a result of a credible single-seal failure shall be designed and assessed for these potential pressure loads. However, propagation of failure by the same mechanism may be considered highly unlikely to (a) the remainder of redundant seals in a series that have been acceptance tested individually prior to flight, (b) seals designed to a factor of safety of 2.5 on the MDP, and (c) seals certified for all operating environments including fatigue conditions.

4.2.1.7.5 Pressure Combined with External Load

In circumstances where pressure loads have a relieving or stabilizing effect on structural-load capability, the minimum value of such relieving loads shall be used and shall not be multiplied by the safety factor in calculating the design yield or ultimate load. Factors of safety for combined load conditions shall be as specified in table 1.

4.2.1.8 Composite and Bonded Structures

Safety and test factors for composite and bonded structures shall be as specified in table 1. An increased factor of safety at discontinuities and bonds is required, and all flight units shall be proof-tested. Hardware shall be designed so that proof tests do not exceed 75 percent of the ultimate stress capability. In addition to initial proof test of the flight article, ablative chambers or nozzles shall demonstrate by qualification test the "end of life" factor specified in table 1 using a hot-fired and fully ablated flight-type test article. Since adhesive strength is sensitive to temperature, the effect of temperature, both higher and lower than nominal, shall be included in establishing the strength allowable for composite or bonded structures.

4.2.1.8.1 Inserts

Inserts in nonmetallic/composite structures are a special case of bonded structures. A series of tests shall be performed to produce an appropriate strength allowable for inserts using flight-like materials and processes. This testing by itself is not sufficient to satisfy the structural testing requirement, which is intended to test the structure in the flight configuration.

4.2.1.9 Factors of Safety

The required factors of safety to be used in the strength analyses and strength tests are specified in table 1. These factors shall be supported by hot-fire testing in addition to static-load tests and pressure tests on qualification and flight units. Verification of the engine primary structure by analysis only is not considered to be a viable option without prior and written approval from the responsible NASA Center. Structural verification plans shall be described in the structural assessment plan (SAP).

4.2.1.10 Margins of Safety

The engine and its components shall be assessed to show non-negative margins of safety using factors of safety specified in table 1. Margin of safety (MS) is the fraction by which "allowable strength" exceeds the "applied load" that has been multiplied by the factor of safety.

$$\text{M.S.} = \frac{\text{Allowable Load}}{(\text{Applied Load})\ (\text{Factor of Safety})} - 1 \geq 0$$

where,

M.S.	=	Margin of safety
Allowable Load	=	Allowable load, pressure, stress, strain, or deflection
Applied Load	=	Actual load, pressure, stress, strain, or deflection at MDC
Factor of Safety	=	Factor from table 1.

4.2.1.11 Other Design Factors

For some applications, it may be appropriate and required to use other design factors such as fitting factors, casting factors, impact factors, etc. in conjunction with the factors of safety specified in table 1.

a. Brazed, welded, and bonded joints require other special factors consistent with their processing and criticality, but these factors shall be at least as severe as those in table 1.

b. Margins of safety on performance-driven clearances (for example, in turbo machinery) are generally calculated using a factor of safety of one. Margins of safety in situations intended to prevent impact, such as an engine fully gimbaled, shall use a factor of safety of 1.4 at MDC loads; i.e., the clearance must be zero or positive at 1.4 X MDC loads.

c. The factors in table 1 shall be used with well-behaved and well-understood materials. For materials not in this category, additional factors may be required. For example, titanium alloys have been shown to be susceptible to failure near the yield load. For titanium alloys, the maximum peak stress (the total concentrated stress from all sources, i.e., MDC loads) shall be less than 80 percent of the material minimum-yield strength.

d. The need for other design factors shall be determined in conjunction with the responsible NASA Center and specified in the SAP.

4.2.1.12 Local Yielding

Local yielding of the engine structure shall be acceptable when ***all*** of the following conditions are met:

a. The structural integrity of the component shall be demonstrated by adequate analysis and/or test.

b. There shall be no detrimental deformations that adversely affect the component/system function.

c. The total load criterion of table 1 is met.

d. The service life requirements are met.

4.2.2 Strength Tests

Strength tests are generally required for components such as rotors, pressure vessels, and major load-carrying structures. The SAP shall identify the hardware that requires structural testing and the type of test to be performed. The types of tests are development, qualification, and acceptance or proof tests. Test factors are specified in table 1. The interfacing structure, through which the loads and reactions are applied to the test unit, shall be simulated in the test at the component level or through analysis.

4.2.2.1 Development Tests

Development tests are required to support new engine designs or concepts. Tests during this phase provide confidence that the new design will accomplish mission objectives. Development test factors are not specified in table 1, but these tests shall be to levels that identify weaknesses in materials and deficiencies of the designs. Some destructive tests are often required. Results from these tests are used to guide the final design. Development test requirements shall be specified in the SAP. Generally, development tests do not suffice for qualification tests unless the tests fulfill all of the requirements in sections 4.2.2.3 and 4.2.2.4.

4.2.2.2 Qualification Tests

Qualification tests are required to verify that flight hardware meets strength requirements. These tests are conducted on flight-configured hardware at conditions (level and duration) more severe than flight conditions to establish that the hardware will perform satisfactorily in the flight environments with sufficient margin. There shall be no detrimental yielding at the MDC yield load and no failure at the MDC ultimate load. The test article shall be instrumented for load, strain, and deflection as appropriate. Structural analysis shall be correlated to the test results, and the final analysis shall be adjusted if indicated. Qualification test requirements shall be specified in the SAP.

In addition to strength tests, a minimum number of hot-fire engine system tests shall occur for the engine to be considered structurally qualified for strength. These tests shall exercise the extremes expected in level and duration for the engine and its components. Each extreme shall be successfully demonstrated without structural failure on at least six distinct engines/components to satisfy structural qualification. If the developer wants to test fewer than six units, the developer shall provide documented technical rationale to the responsible government structural organization and obtain approval before committing to the reduced test program.

4.2.2.3 Acceptance/Proof Tests

All engine pressure vessels, pressurized components, major pressure-loaded components, and major rotating hardware shall be proof-tested to ensure satisfactory workmanship and material quality. Proof (spin, pressure, or load) tests are required for all brazed, composite, or bonded structures. In cases where there are significant load conditions in addition to pressure, a combined proof-pressure and external-loading test shall be conducted, or the test pressure shall be increased to encompass all loads. Nondestructive evaluation (NDE) shall be performed before and after proof-testing. Parts must be designed so that no detrimental yielding occurs during proof tests and so that proof loads will be limited to 95 percent on net section yield and 75 percent on net section ultimate. Proof factors are specified in table 1. Note that fracture control may require a higher test factor than those listed in table 1 if the proof test will be used for flaw screening. Proof-test requirements shall be specified in the SAP.

In addition to component proof-tests, each engine shall be hot-fire tested at nominal level and duration to be considered structurally acceptable. Hot-fire engine tests are also required to qualify the engine for life. Each engine program shall define these tests. The number of engines, the number of tests, and the total accumulated time shall be included in the test program definition. Engine purpose, reliability, complexity, mission life, etc. shall be used to determine the extent of these tests.

4.2.2.4 Test-Level Corrections for Environment

Qualification and proof tests shall be conducted in the operational environment. If testing in the operational environment is not feasible, tests can be performed in a non-operational environment if an environment correction factor (ECF) is applied. An ECF is a factor to be multiplied by the test load to compensate for the environmental effect on the strength (E, Fty, Ftu, etc.) capability at test conditions versus the operating condition.

$$\text{ECF} = \frac{\text{Strength capability at test condition}}{\text{Strength capability at operating condition}}$$

4.2.3 Factors of Safety for Analysis and Strength Test Factors

The minimum factors of safety and minimum test factors to be used in the assessment of NASA liquid fueled space propulsion system engines and their components are given in table 1.

4.2.4 Life Analysis

4.2.4.1 Material Properties

Generally, material properties for life analysis shall be as specified in section 4.2.1.2. In cases where A or B basis is not available and cannot be feasibly generated, other lower-bound approaches to fatigue and creep data may be used with the written approval of the responsible NASA Center.

4.2.4.2 Loads Spectra

A design-load history shall be developed in sufficient detail for the cumulative damage to be analytically predicted for all applicable components. The component-load history shall include the number of cycles or time at each significant load-level considering all phases of fabrication, assembly, testing, transportation, ground handling, checkout, firing, launch, flight, return, etc. Both low- and high-cycle fatigue loads, sustained loads, preloads, and assembly loads shall be considered in the life assessment. Loads from mechanical, thermal, pressure, and atmospheric sources shall be included as appropriate. The life assessments below shall be made using this significant load history and the material properties corresponding to the environment of each event.

4.2.4.3 Creep Analysis

All flight hardware structures shall be designed to preclude cumulative strain as a function of time, i.e., creep, which could result in rupture, detrimental deformation, or collapse, (e.g., buckling) of compression members during the design service life. Materials shall be selected to preclude accumulated damage from creep in the engine environment. If selecting a structural material that exhibits creep phenomena in the engine environment is unavoidable, then all structural elements subject to creep shall be assessed to demonstrate the following factors:

a. Creep Analysis Factor. Multiply the limit stress/strain by a minimum factor of 1.15 prior to entering the design curve to determine creep life.

b. Service Life Factor. The analysis shall demonstrate a minimum calculated life of 10.0 times the service life.

4.2.4.4 Fatigue Analysis

The engine and its components shall be assessed for low-cycle fatigue (LCF) and high-cycle fatigue (HCF) using the following guidelines:

a. For cyclic loads to varying levels, such standard methods as Miner's Method shall be used to determine the combined damage. For alternating load combined with a mean load, such standard methods as the Modified Goodman Line shall be used to determine the combined effect.

b. All structural elements shall be designed and analyzed to demonstrate the following factors:

(1) Fatigue Analysis Factor (FAF). A FAF shall be multiplied by the limit stress/strain prior to entering the S-N design curve to determine the low-cycle/high-cycle life. The FAF shall be

FAF = 1.25 Rotating components
FAF = 1.15 Non-rotating components

(2) Service Life Factor. The LCF analysis shall demonstrate a minimum calculated life of 4.0 times the service life. The HCF analysis shall demonstrate a minimum calculated life of 10.0 times the service life.

(3) Stress Concentrations. The alternating and mean stress/strain shall include the effects of stress concentration factors when applicable.

All structural components subject to combined fatigue and creep shall be evaluated using such standard methods as Miner's accumulated damage procedure for final life predictions.

4.2.4.5 Fatigue Tests

Fatigue tests generally will be either development or qualification tests.

4.2.4.5.1 Development Fatigue Tests

Development fatigue tests are used to guide the design. Levels and duration shall be sufficiently severe to identify any weakness and provide confidence that the final design will pass qualification. Development test requirements shall be specified in the SAP.

4.2.4.5.2 Qualification Fatigue Tests

Qualification fatigue tests may be deemed required if analysis in accordance with section 4.2.4.4 cannot be confidently accomplished. These tests are conducted on flight-configured hardware and in the appropriate flight environment. The component is tested at the MDC alternating and mean stresses for 4 times the number of cycles established in section 4.2.4.2. The test article shall be instrumented for load, strain, and deflection as appropriate. Qualification fatigue test requirements shall be specified in the SAP.

4.2.5 Documentation

The following documentation requirements are the minimum required to fully document the strength and life assessments for an engine program. These documents shall be used to develop data requirements for specific programs.

4.2.5.1 Structural Assessment Plan

The responsible organization shall submit the SAP as early as possible but no later than preliminary design review (PDR) and shall update it at significant program milestones and as the structural assessment approaches evolve. The SAP shall specify how the particular engine program plans to satisfy the requirements of this document. The SAP would include topics such as which pressures are applicable (MEOP, MDP, MDC) for analysis, the loads spectra, etc., for the engine being assessed. The SAP shall also describe the development, qualification, and acceptance/proof test approaches for the specific engine hardware.

4.2.5.2 Analyses and Test Reports

The responsible organization shall document analyses and/or tests to show that the hardware complies with program requirements. The responsible organization shall submit strength and life analyses as well as development, qualification, and acceptance/proof test reports that will verify the capability of hardware to meet mission requirements with factors of safety as specified in this document and in the SAP. Reports shall be in hard copy and electronic format. The electronic reports shall be assembled using a common commercially available software package. Sufficient detail shall be included in the reports so that the results can be recreated. All material properties, loads, and other data from external sources shall contain references to the data source.

4.2.5.2.1 Analysis Reports for PDR

Preliminary strength and life analyses shall be submitted as part of the PDR data package. These analyses shall be sufficiently detailed to establish the structural integrity of all major structural elements and the credibility of weight calculations.

4.2.5.2.2 Analysis Reports for Critical Design Review (CDR)

Current strength and life analysis reports shall be submitted as part of the CDR data package. These reports shall fully substantiate the structural integrity of each detailed part and provide the basis for the stress signatures on the drawings.

4.2.5.2.3 Test Reports

Test plans shall be submitted 30 working days prior to the test and test result reports, 45 working days after the test, or as specified in the SAP. The intent to run a specific test shall be declared in the SAP. Test plans shall specify test success criteria, and test results shall correlate the test outcomes with the analysis predictions.

4.2.5.2.4 Final and As-Built Assessment Report

The responsible organization shall provide a final and as-built assessment of the flight hardware. This assessment shall be accomplished using analyses and test results to establish the flight worthiness of actual flight hardware. The report shall include assessment of significant deviations in materials, workmanship, etc. from the design as well as analytical adjustment needed as indicated by test results. Margins of safety shall be updated for the final and as-built configurations.

Table 1—Minimum Analysis Factors of Safety and Strength Test Factors

Engine Hardware Type	Load	Mode of Failure	Analysis Factor of Safety [1]	Test Factors [2]	
				Qualification	Acceptance/ Proof [3]
Metallic Structures and Components					
Yield	mechanical only	net section	1.10 [4]	NA	NA
Ultimate	mechanical only	net section	1.40	1.40	NA
Ultimate	MDC	stability	1.40	1.40	1.20
Ultimate-pressure or rotation	MDP or spin	net section	1.50	1.50	1.20 [5, 6]
Ultimate	MDC	point strain	2.00 [4]	1.40	1.20
Pressurized components (pressure vessels, lines, fittings, fluid return sections and hose, bellows, etc.)	MEOP, MDP, or MDC as applicable	MIL-STD-1522 or ANSI/AIAA S-080, ANSI/AIAA S-081, AFSPCMAN 91-710			
Fasteners and Preloaded Joints					
Yield	MDC	net section	1.10 [4]	NA	NA
Ultimate	MDC	net section	1.40	1.40	1.20
Joint Separation	MDC	separation	1.20	1.20	1.20
- Safety Critical [7]	MDC	separation	1.40	1.40	1.20
Composite and/or bonded structures and components – ultimate strength					
Uniform areas	MDC	point stress	1.40	1.40	1.20 [5]
Stress concentration areas	MDC	point stress	2.00	1.40	1.20 [5]
Bonds/joints	MDC	point stress	2.00	1.40 [5]	1.20 [5]
Ablatives	MDC	point stress	1.70 [8]	1.40 [5, 8]	1.20 [5]
Pressure checkout with personnel present					
Yield	checkout pressure	Note 9	1.50 [4]	NA	NA
Ultimate	checkout pressure	Note 9	2.00	NA	NA

Notes:

1. Margins must be written using the specified analysis factor of safety for all the specified loads and modes of failure.
2. Minimum factors which shall be used in the test program to be defined in the SAP for a specific project.
3. Fracture control may require higher factors if the proof test will be used for flaw screening.
4. For titanium alloys, the maximum peak stress (the total concentrated stress from all sources, i.e., MDC loads) shall be less than 80 percent of the material minimum yield strength.
5. These tests are always required.
6. Test pressure = MDP x 1.20 x ECF ≥ 1.05 x MDP
   Test speed = $\sqrt{(\text{MDC speed}^2 \times 1.20\ \text{ECF})} \geq \sqrt{(\text{MDC speed}^2 \times 1.05)}$
7. Joints for which separation would be a catastrophic event.
8. Analysis and test factors apply at end of life. Qualification test occurs on a hot-fired (fully ablated) flight-type test article.
9. Net section for metallics, point stress on ultimate only for composites or adhesive bonds.